Response of terrestrial aridity to global warming

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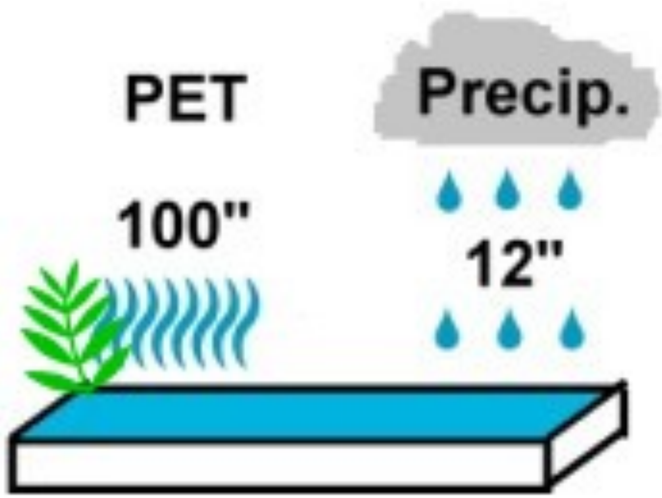
Introduction

- Potential evapotranspiration (*PET*): The maximum amount of water capable of being lost from the surface for given atmospheric condition with well supplied surface water (i.e., the evaporative demand of the atmosphere).

- Aridity index (UNEP 1992):

  $AI = P/PET$

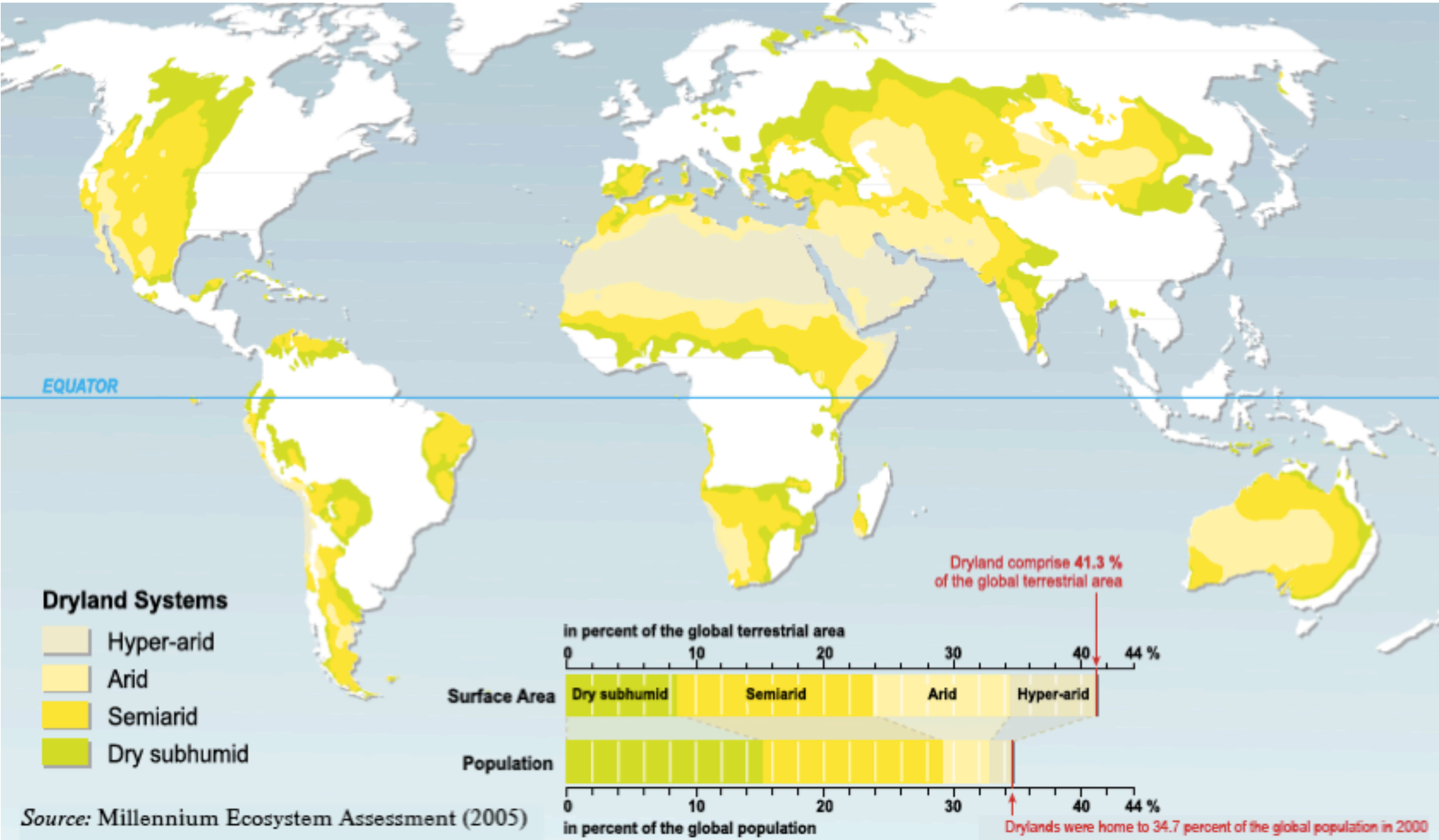


e.g., at Tucson, USA

$P/PET = 0.12$

- Drylands are regions with *P/PET* < 0.65, which are further divided into (UNEP 1992; Hulme 1992):
  - Hyper-arid: *P/PET* < 0.05
  - Arid: 0.05 < *P/PET* < 0.20
  - Semid-arid: 0.20 < *P/PET* < 0.50
  - Dry subhumid: 0.50 < *P/PET* < 0.65

Distribution of World's Drylands



Source: Millennium Ecosystem Assessment (2005)

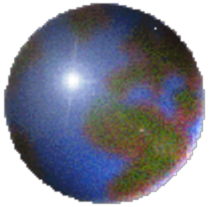
- How does terrestrial aridity in terms of *P/PET* respond to anthropogenic climate change?

A view of dryland (with village in the background) in the Sahel, southern Niger

- Previous studies focus on change in precipitation, as typical in high-profile reports (e.g., IPCC 2007, 2014), which may not tell the whole story – or perhaps even the main story – of hydrological change.

- Most studies of terrestrial dryness focus on droughts (e.g., Dai 2013), rather than on the background aridity changes.

- Drought region versus arid region
    - Anomaly (extreme) versus mean state (background climatology)



- Introduction
- A drier terrestrial climate
  - Global dryland expansion
- Past, present, and future
- Conclusions

A drier terrestrial climate

- Observational data for 1948-2010
  - *T* and *P*: CPC and UD
  - *R*, *RH* and *u*: GLDAS and the 20th Century Reanalysis
- Model data for 1948-2100
  - 27 CMIP5 GCMs with historical forcings for 1948-2005 and RCPs 8.5 and 4.5 for 2006-2100
  - The simulated data were statistically downscaled to 0.5 degree resolution
- CMIP5 transient CO_2 1%/yr increase experiments
  - 25 CMIP5 GCMs to doubling CO_2

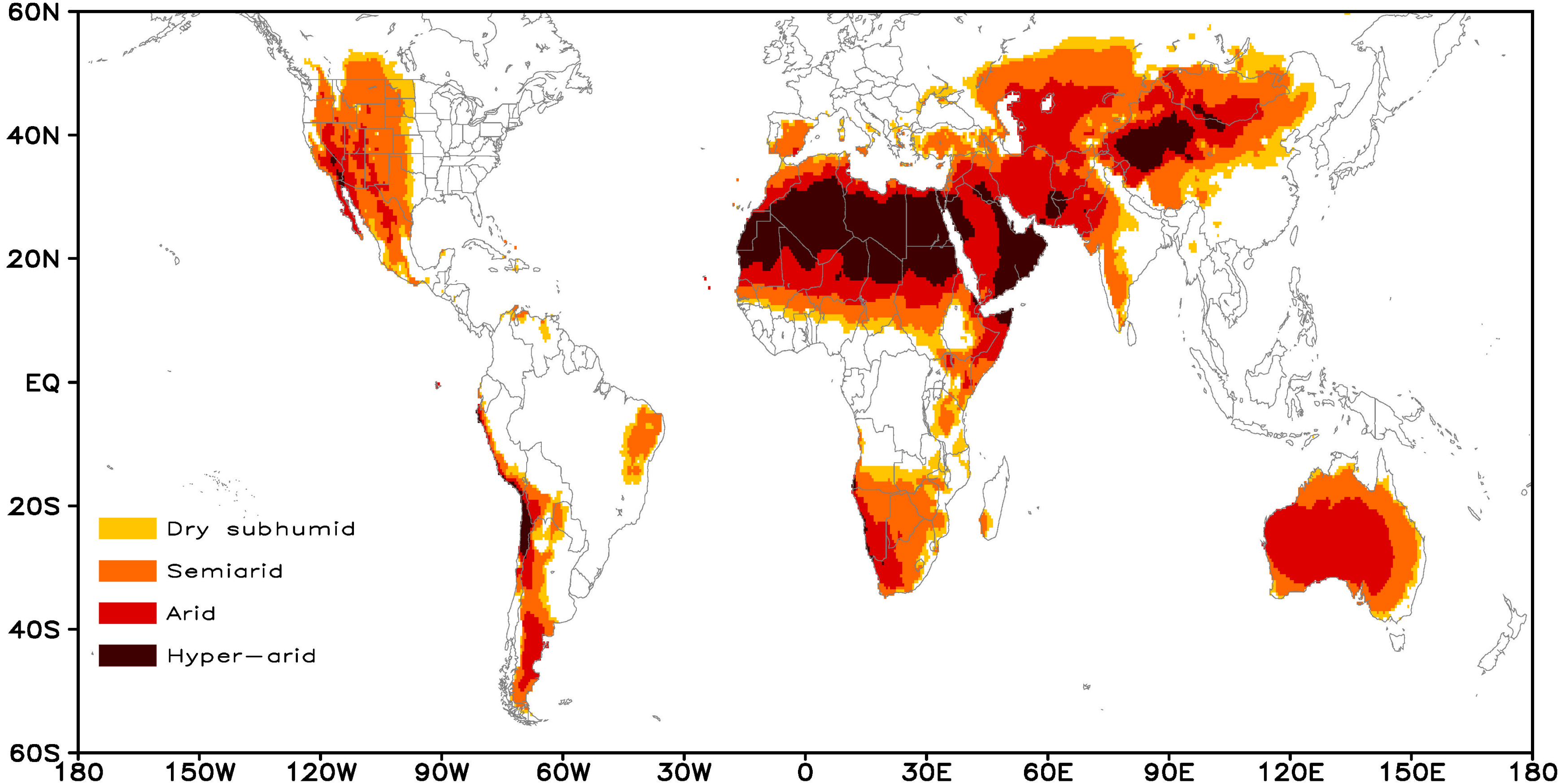
PET algorithm

- The *PET* is based on the Penman-Monteith (PM) algorithm (Maidment 1993; Allen et al. 1998; Sheffield et al. 2012; Scheff & Frierson 2014):

$$PET = \frac{(R_n - G)\Delta(T_a) + \rho_a c_p e^*(T_a)(1 - RH)C_H \mid u \mid}{\Delta(T_a) + \gamma(1 + r_s C_H \mid u \mid)} / L_v$$

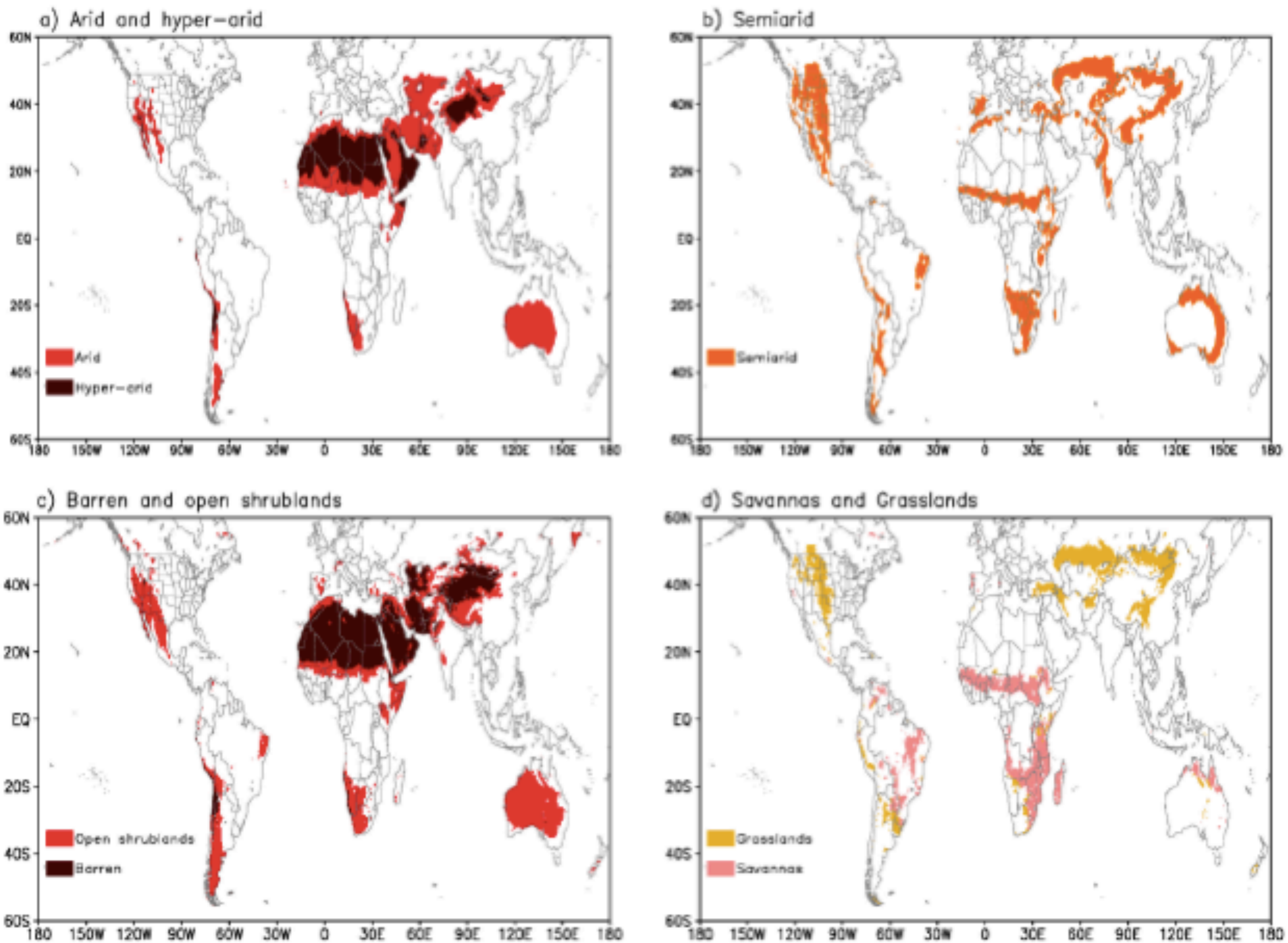
where R_n-G is the surface available energy, T_a temperature, RH relative humidity, and u wind; e* is saturated water vapor pressure, $\Delta = de^*/dT$, C_H transfer coefficient (4.8×10^{-3}), r_s bulk stomatal resistance under well-water conditions (70 s/m).

Global dryland distribution for 1961-1990 climatology



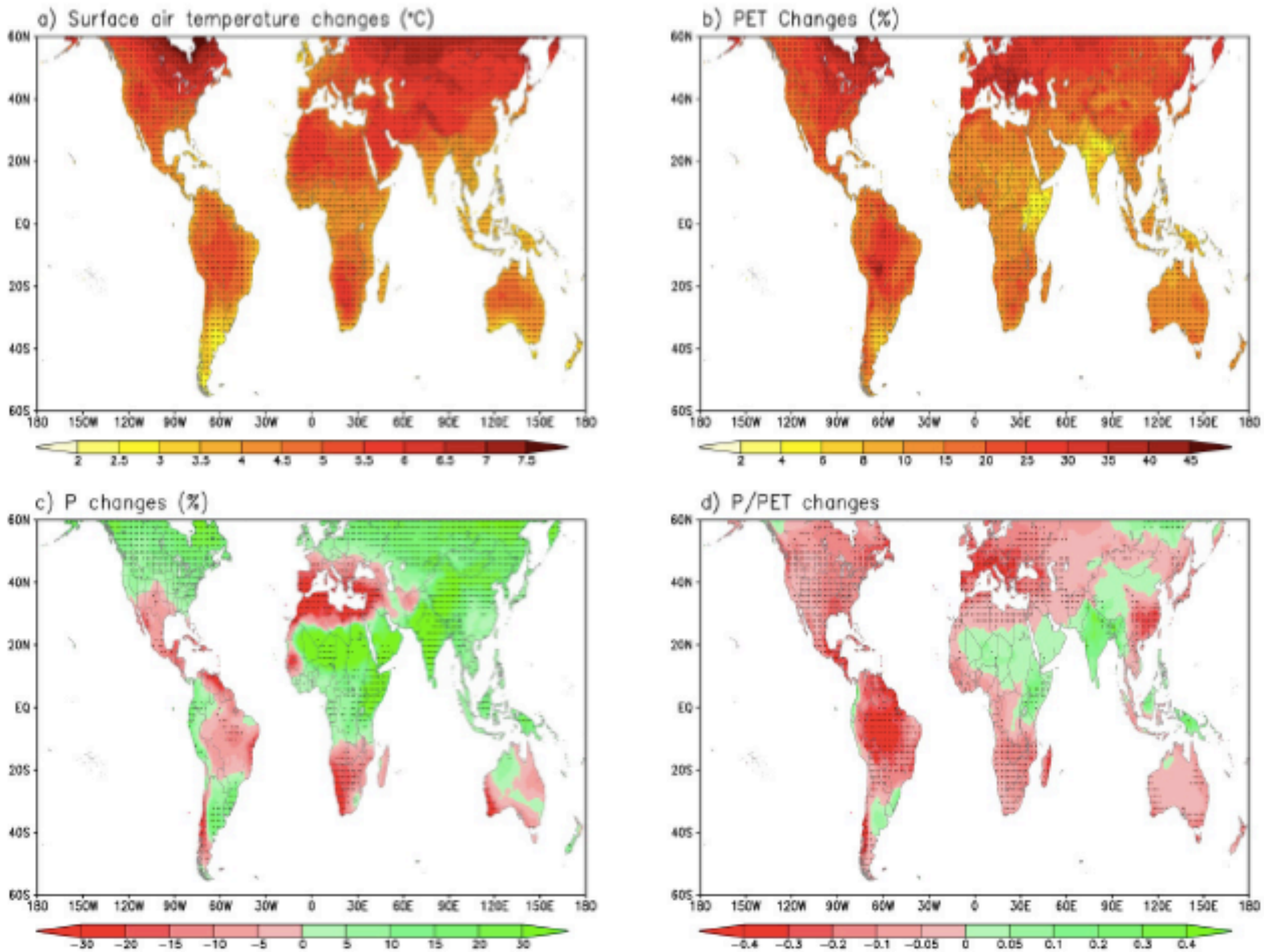
Feng & Fu (2013)

Global dryland distributions versus vegetation types from MODIS



Feng & Fu (2013)

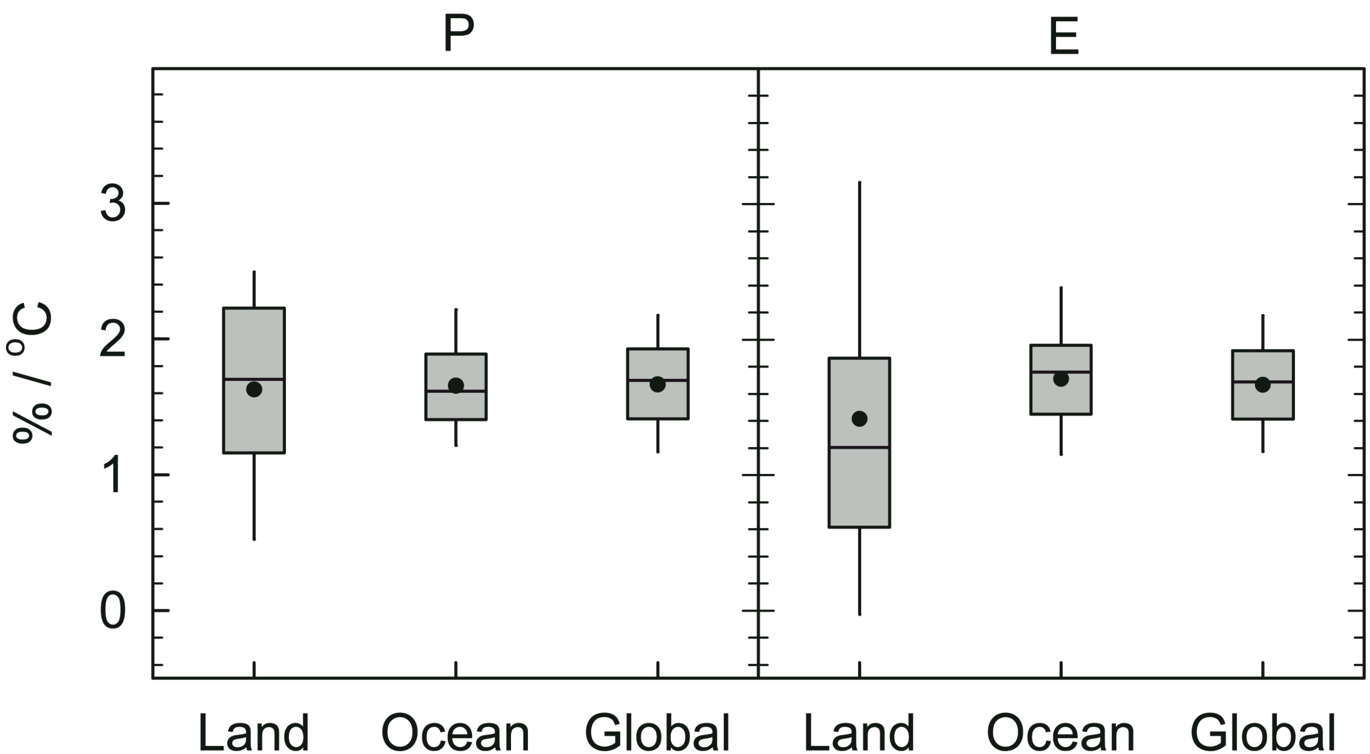
Changes in (a) surface air temperature, (b) *PET*, (c) precipitation, and (d) *P/PET* (1961-1990 to 2071-2100) under scenario RCP85



Feng & Fu (2013)

Why do we expect a drier climate under global warming

- As the globe warms global average rainfall increases (e.g., Allen and Ingram, 2002).



Fu & Feng (2014)

The percentage change in *P/PET* can be written as

$$\Delta\left(\frac{P}{PET}\right)\Big/\left(\frac{P}{PET}\right) \approx \frac{\Delta P}{P} - \frac{\Delta PET}{PET}$$

Noting a similar rate of percentage increase in P over land to that in E over ocean, we have

$$\Delta\left(\frac{P}{PET}\right)\Big/\left(\frac{P}{PET}\right) \approx \left(\frac{\Delta E}{E}\right)_{Ocean} - \frac{\Delta PET}{PET}$$

- The Penman-Monteith algorithm can be used to estimate the actual E over ocean by setting $r_s = 0$ and using a C_H of 1.5×10^{-3} (Richter and Xie 2008), i.e.,

$$E = \frac{(R_n - G)\Delta(T_a) + \rho_a c_p e^*(T_a)(1 - RH)C_H |u|}{\Delta(T_a) + \gamma} / L_v$$

Table. Comparison of annual mean evaporation (*E*) and its percentage change rate and surface stability ($T_a - T_s$) change rate over ocean estimated using the PM algorithm and those from the GCMs.

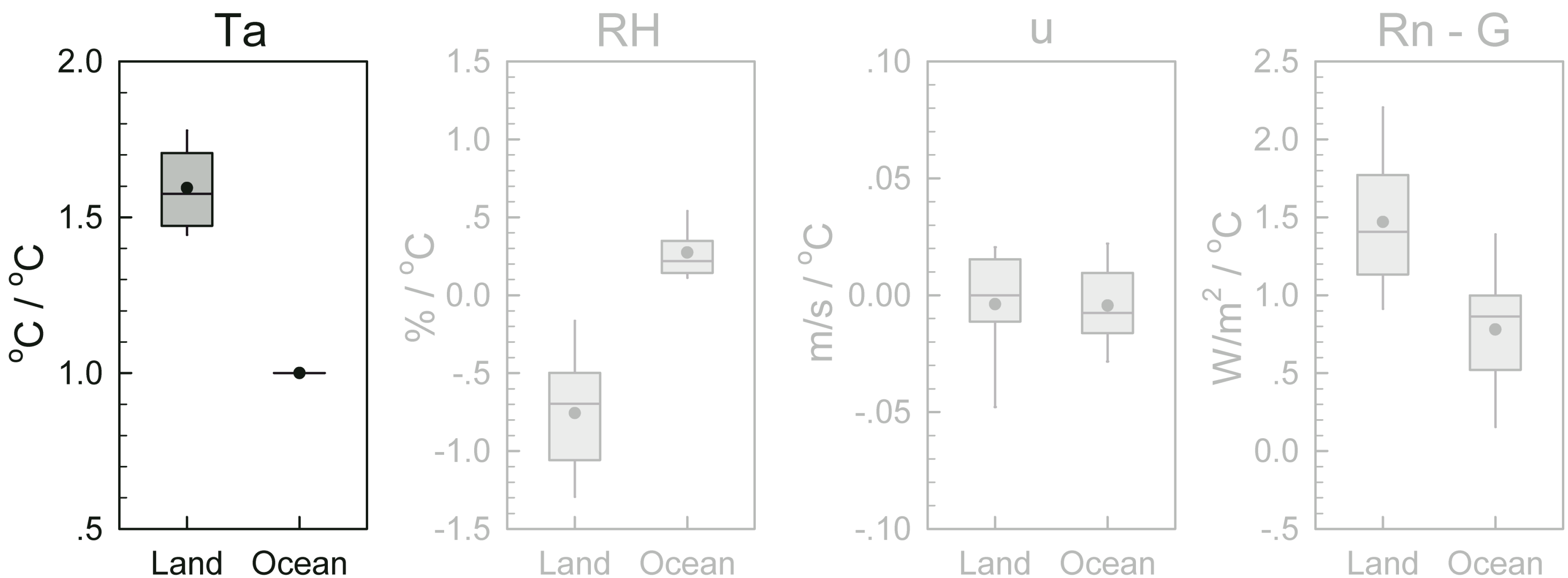
	E (mm)	Percentage change rate in *E* (%/°C)	Change rate in $T_a - T_s$ (°C/°C)
Penman-Monteith	1267 (90)	1.92 (0.39)	0.07 (0.03)
Directly from GCMs	1300 (62)	1.71 (0.40)	0.06 (0.02)

Fu & Feng (2014)

- Since the PM algorithm can be applied to both *PET* over land and *E* over ocean, we can examine the change in *P/PET* in the framework of the *PET* by comparing its changes over land and ocean.

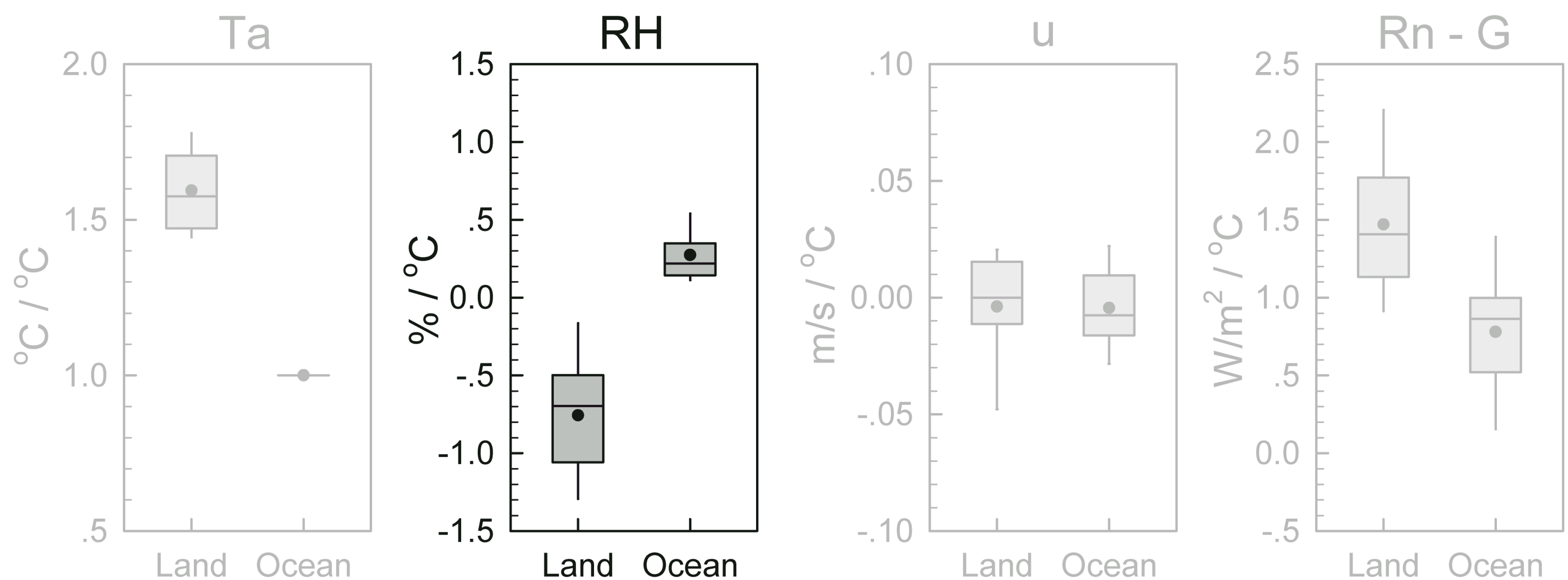
- Both *PET* over land and *E* over ocean are a function of surface air temperature (T_a), relative humidity (*RH*), wind speed (*u*), and available energy (R_n-G).

- Ingredient one: Land surface warms on average, about 50% more than oceans (e.g., Manabe et al. 1992; Joshi et al. 2008)



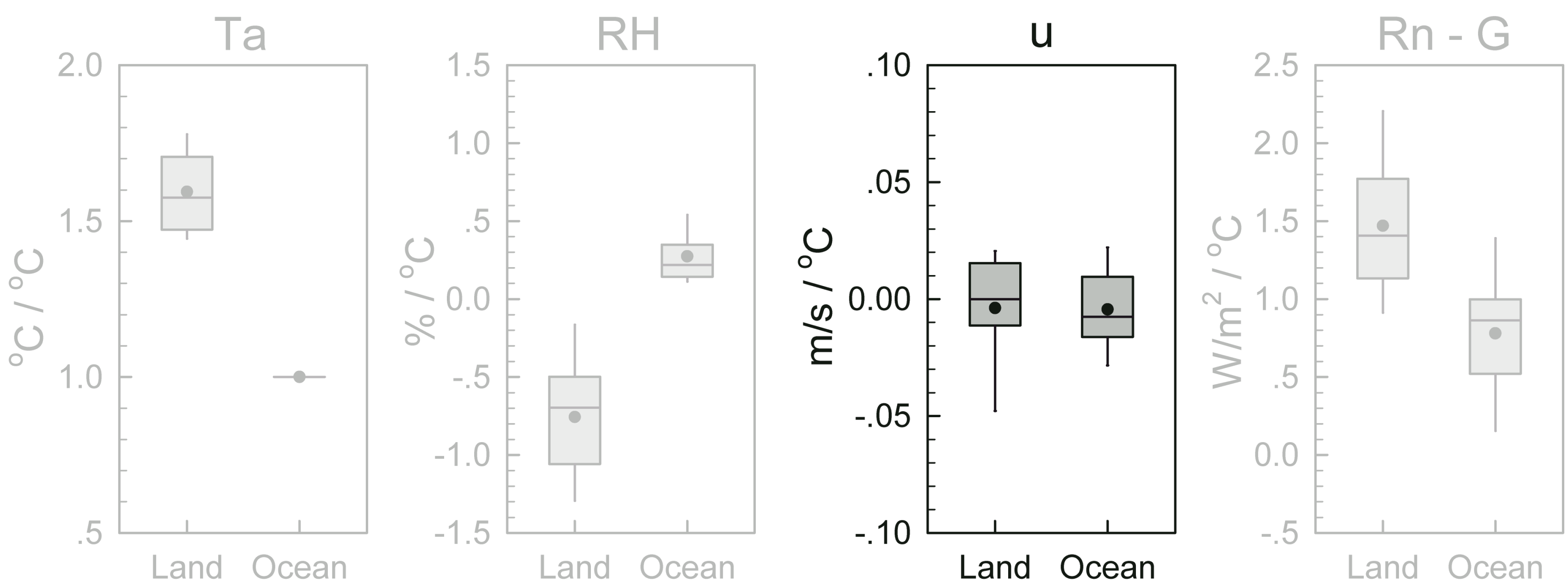
Fu & Feng (2014)

- Ingredient two: Reduced relative humidity near the surface over land but increased RH over ocean (e.g., Simmons et al. 2010; O'Gorman and Muller 2010; Sherwood and Fu 2014)



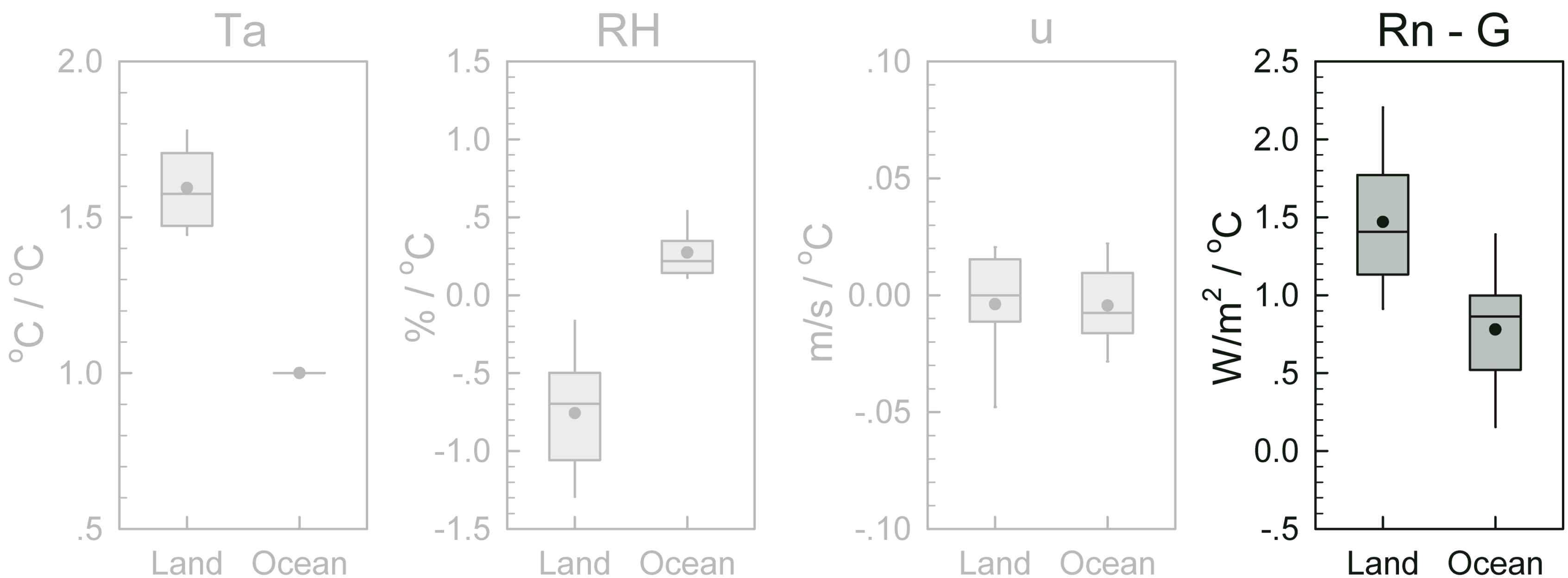
Fu & Feng (2014)

- The surface winds change little over both land and ocean.



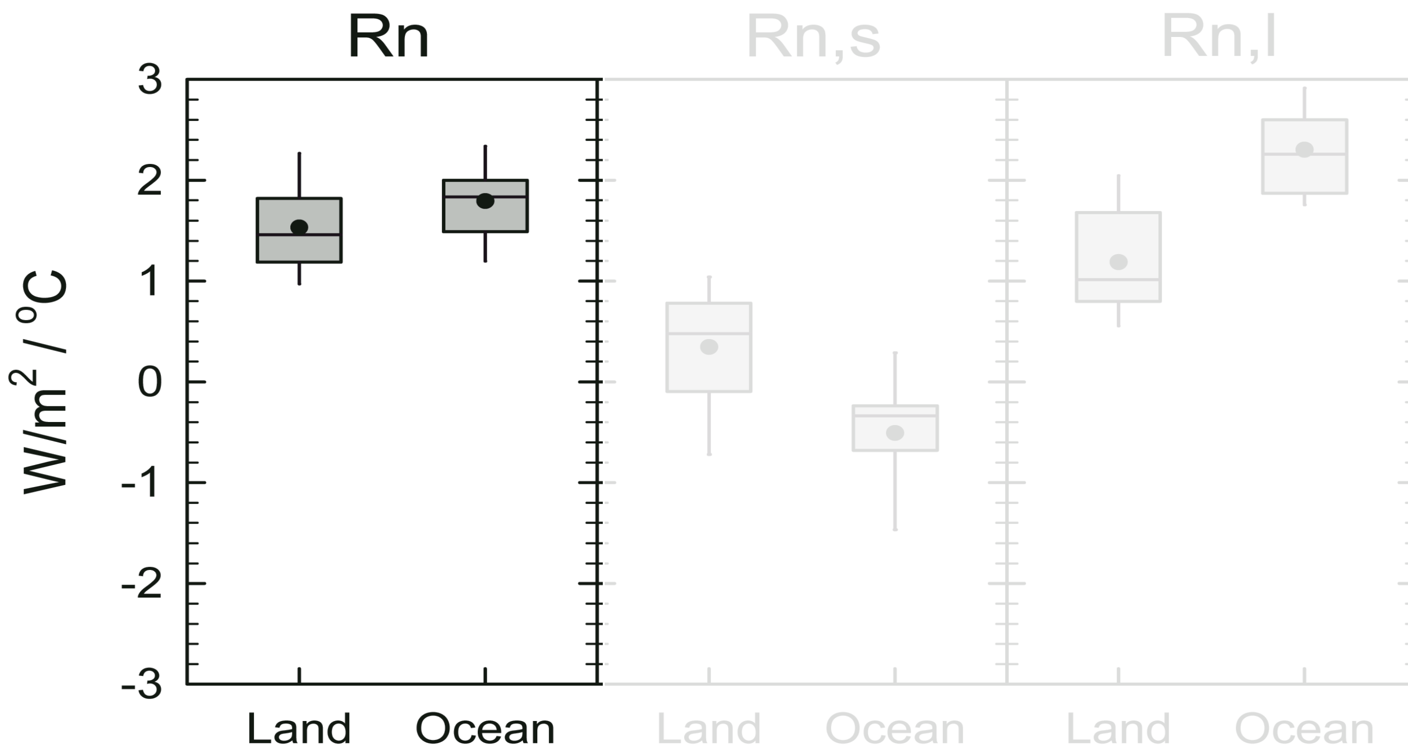
Fu & Feng (2014)

- Ingredient three: Part of increased net downward radiation is transported to deep ocean (e.g., Hansen et al. 2005; Johnson et al. 2011; Loeb et al. 2012)



Fu & Feng (2014)

- Change of net radiative energy budget at the surface



Fu & Feng (2014)

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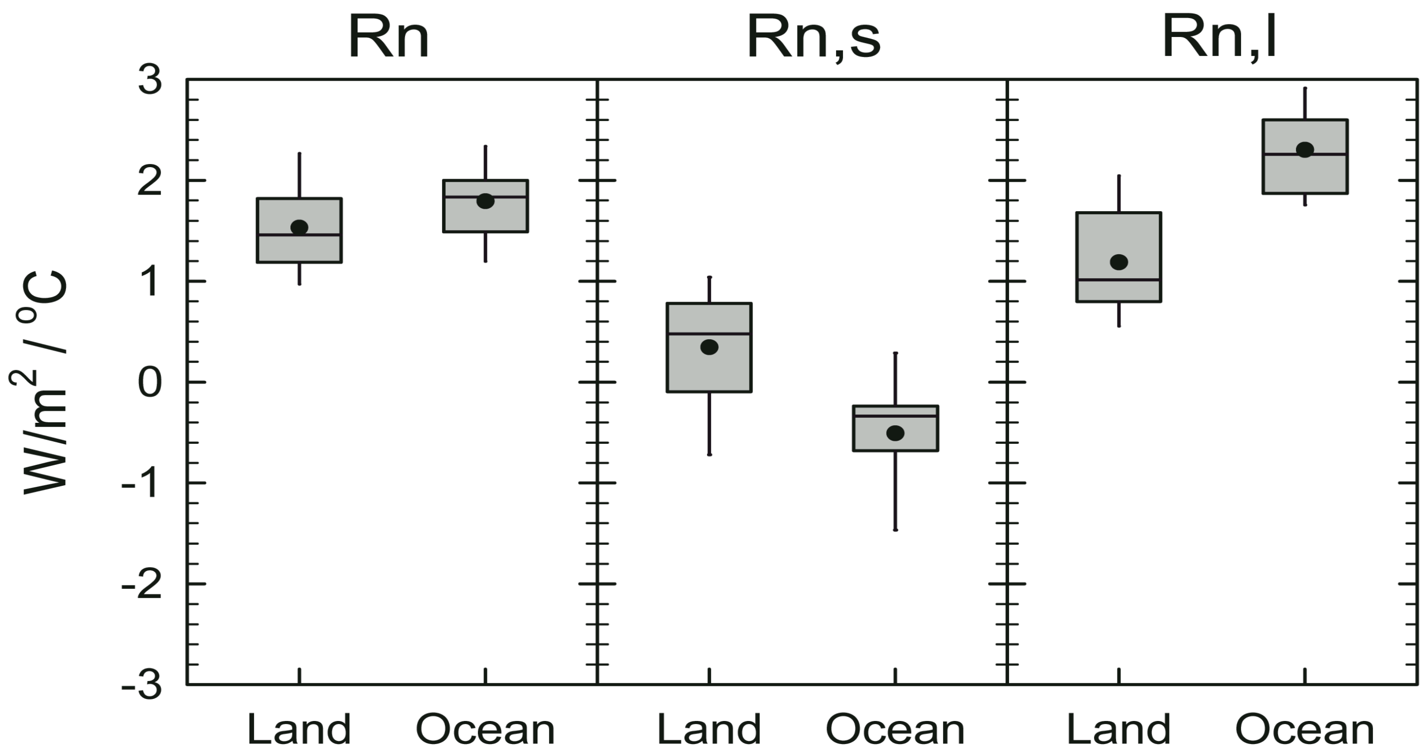
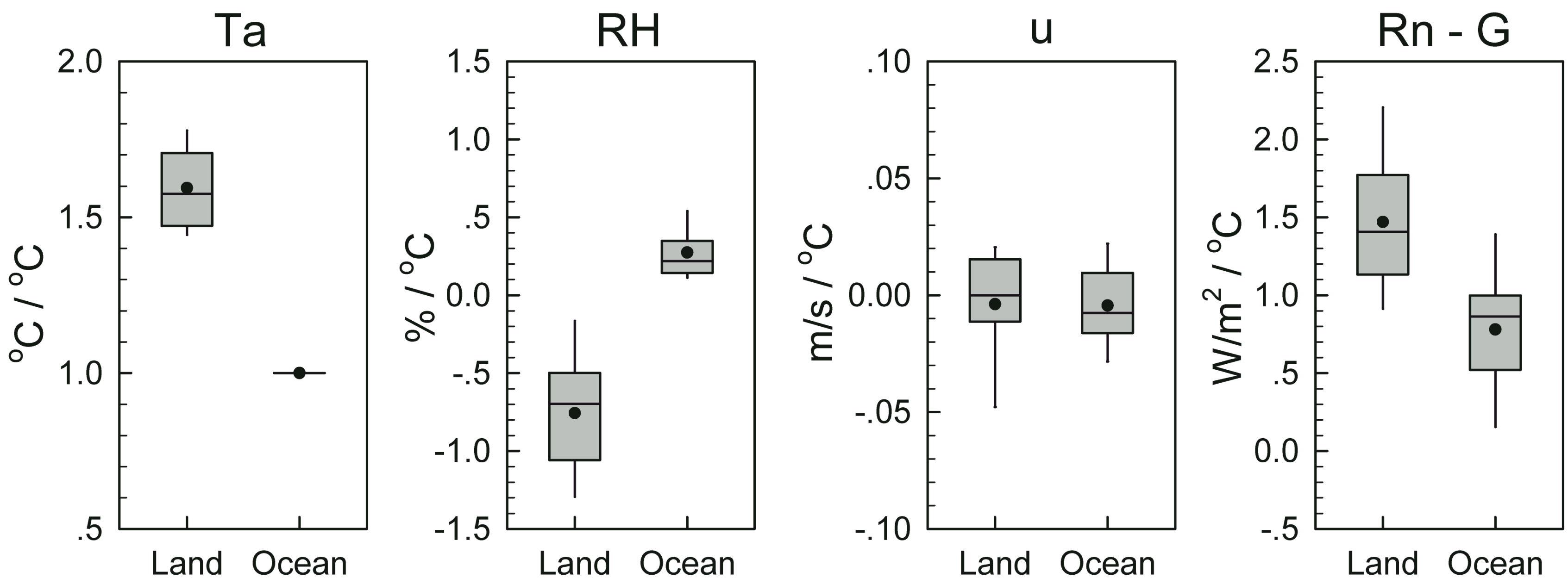


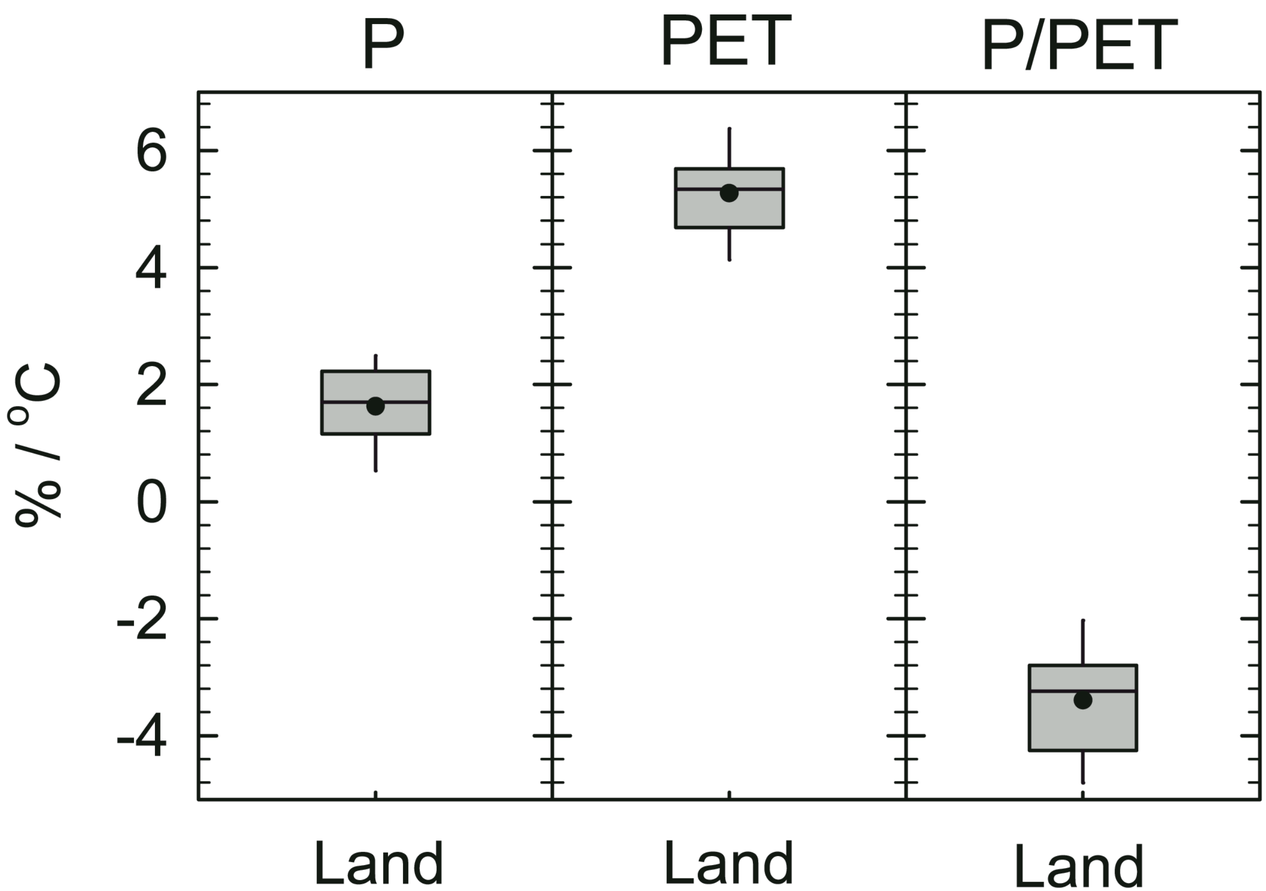
Fu & Feng (2014)

- Ingredients that contribute to a drier terrestrial climate in a warming world

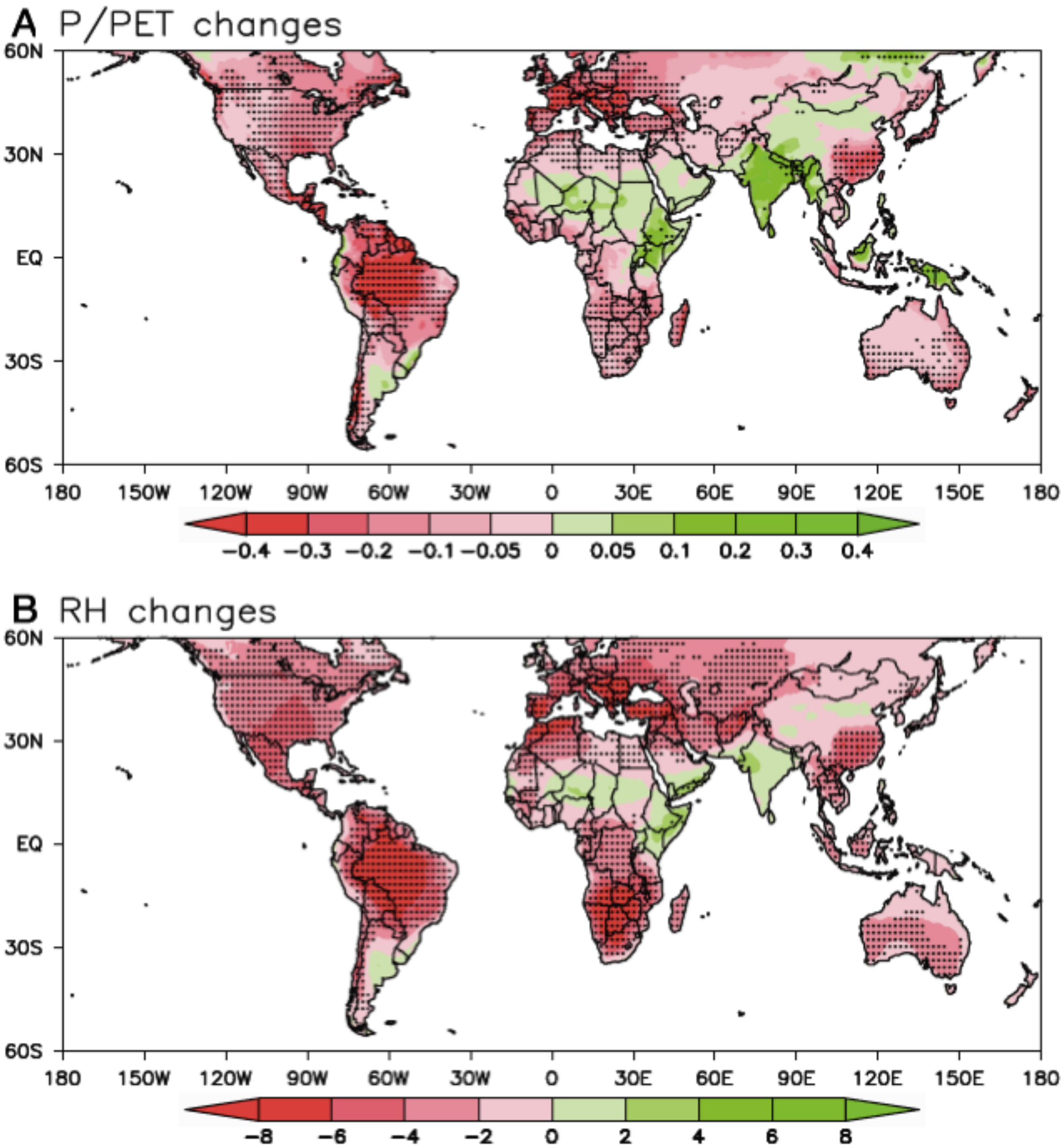


Fu and Feng (2014)

- Our scale analysis shows an averaged decrease of *P/PET* by ~3.4%/K over land



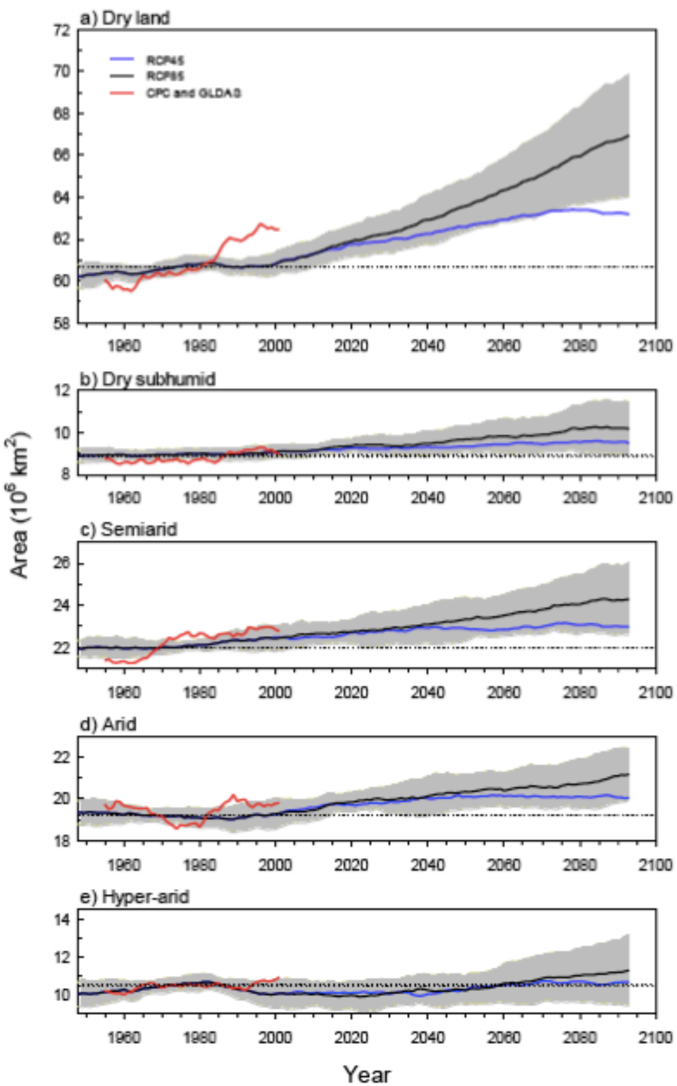
Fu & Feng (2014)



Changes in (a) *P/PET* and (b) *RH* (1980-1999 to 2080-2099) under scenario RCP85

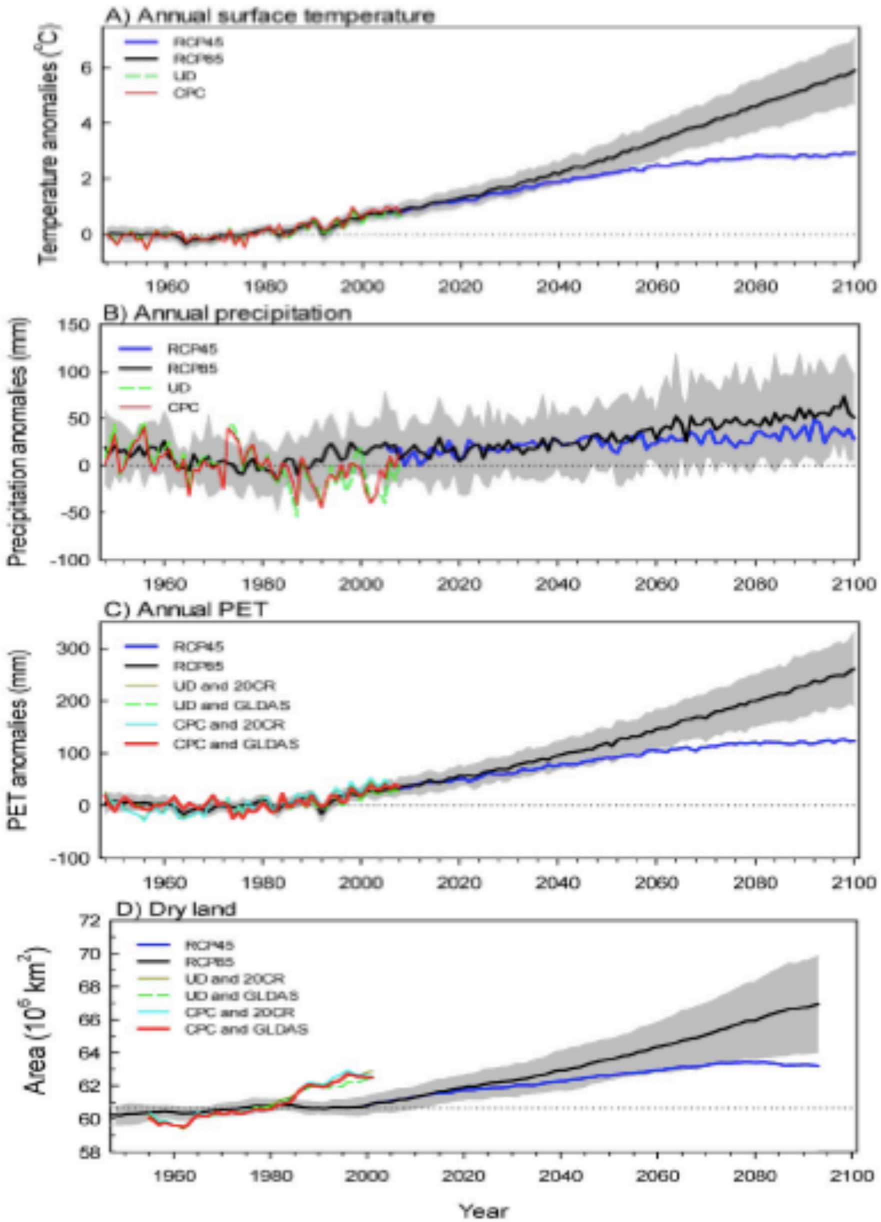
Sherwood & Fu (2014)

Global dryland expansion



Temporal variations of global dryland areas for (a) the total and individual components of (b) dry subhumid, (c) semiarid, (d) arid, and (e) hyper-arid regions.

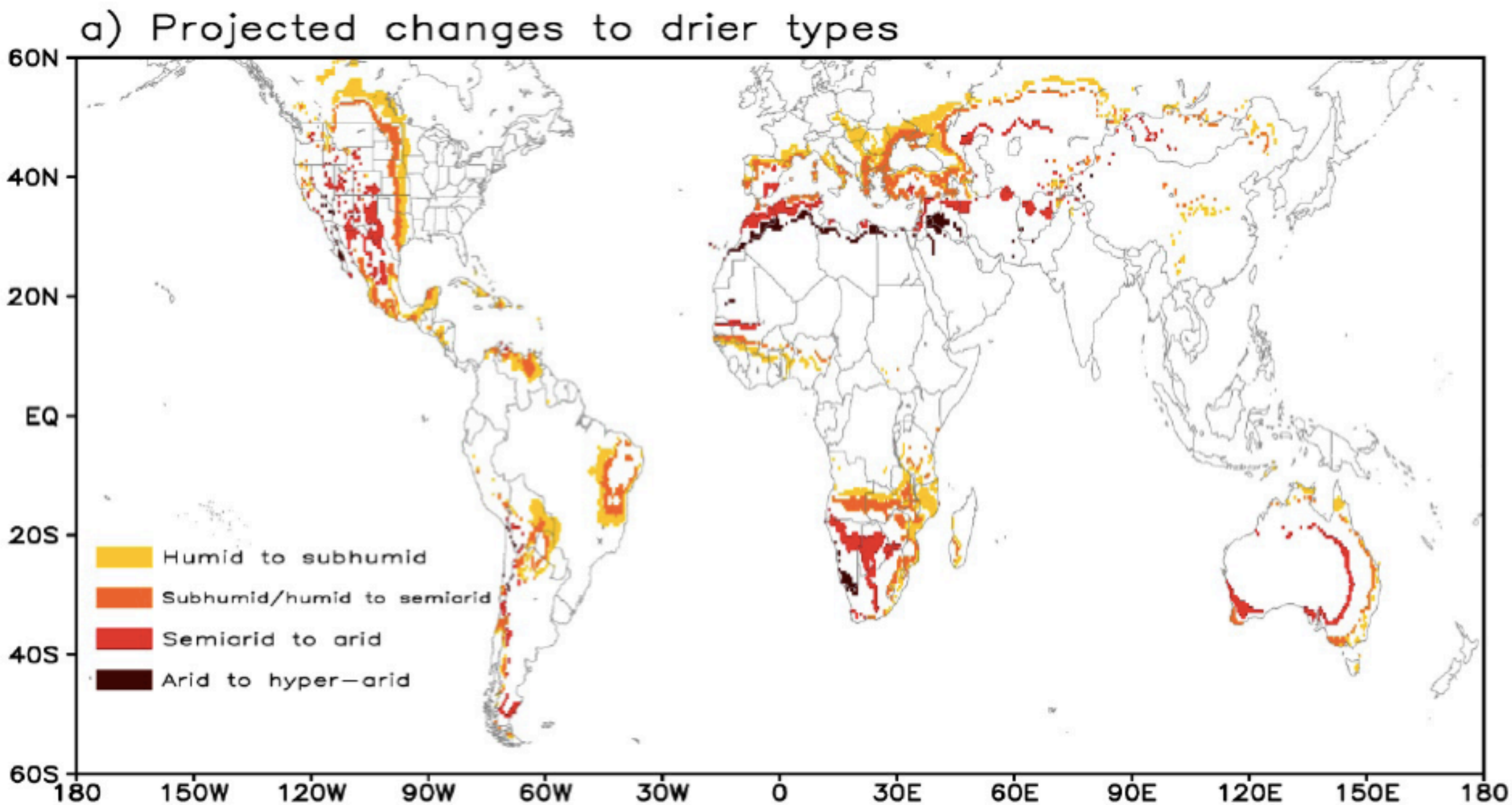
Feng and Fu (2013)



Temporal variations of annual mean (a) surface air temperature, (b) precipitation, and (c) *PET,* averaged over land between 60°N and 60°S, and (d) total area of global drylands.

Feng and Fu (2013)

Changes in dryland coverage to drier types (1961-1990 to 2071-2100) under scenario RCP8.5



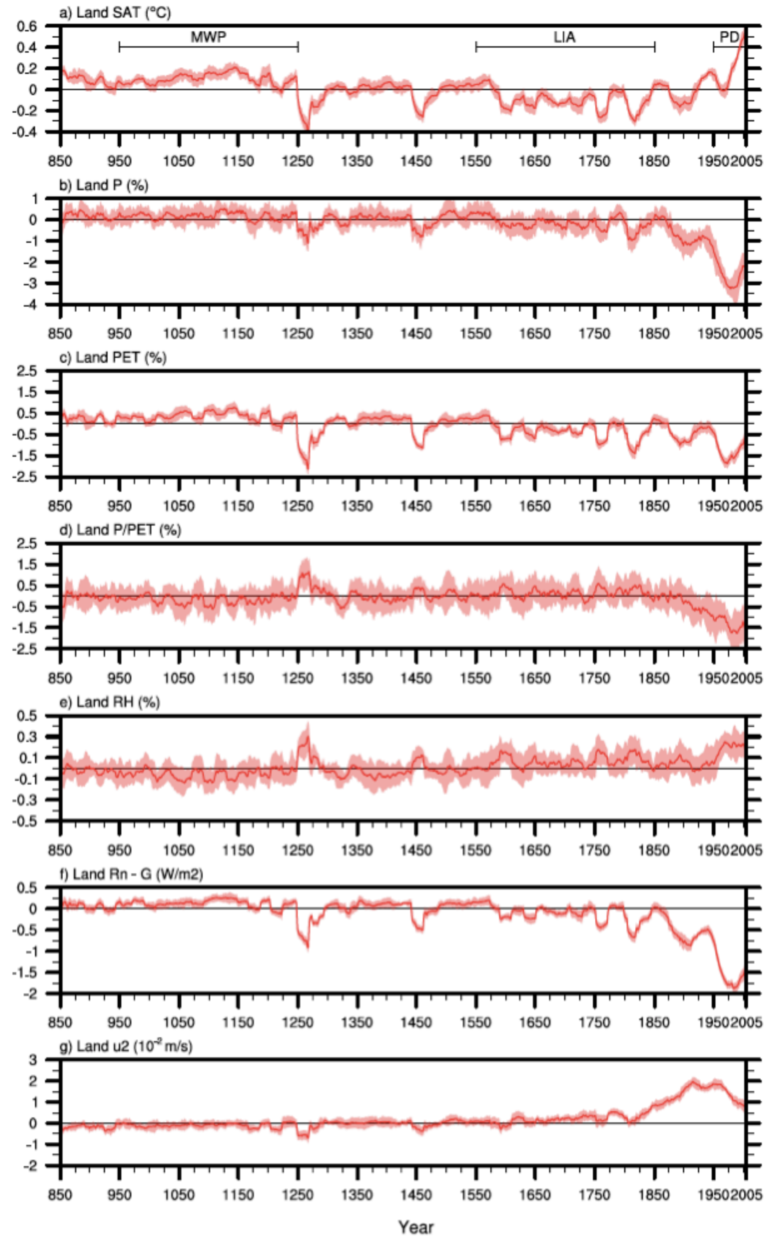
Feng and Fu (2013)

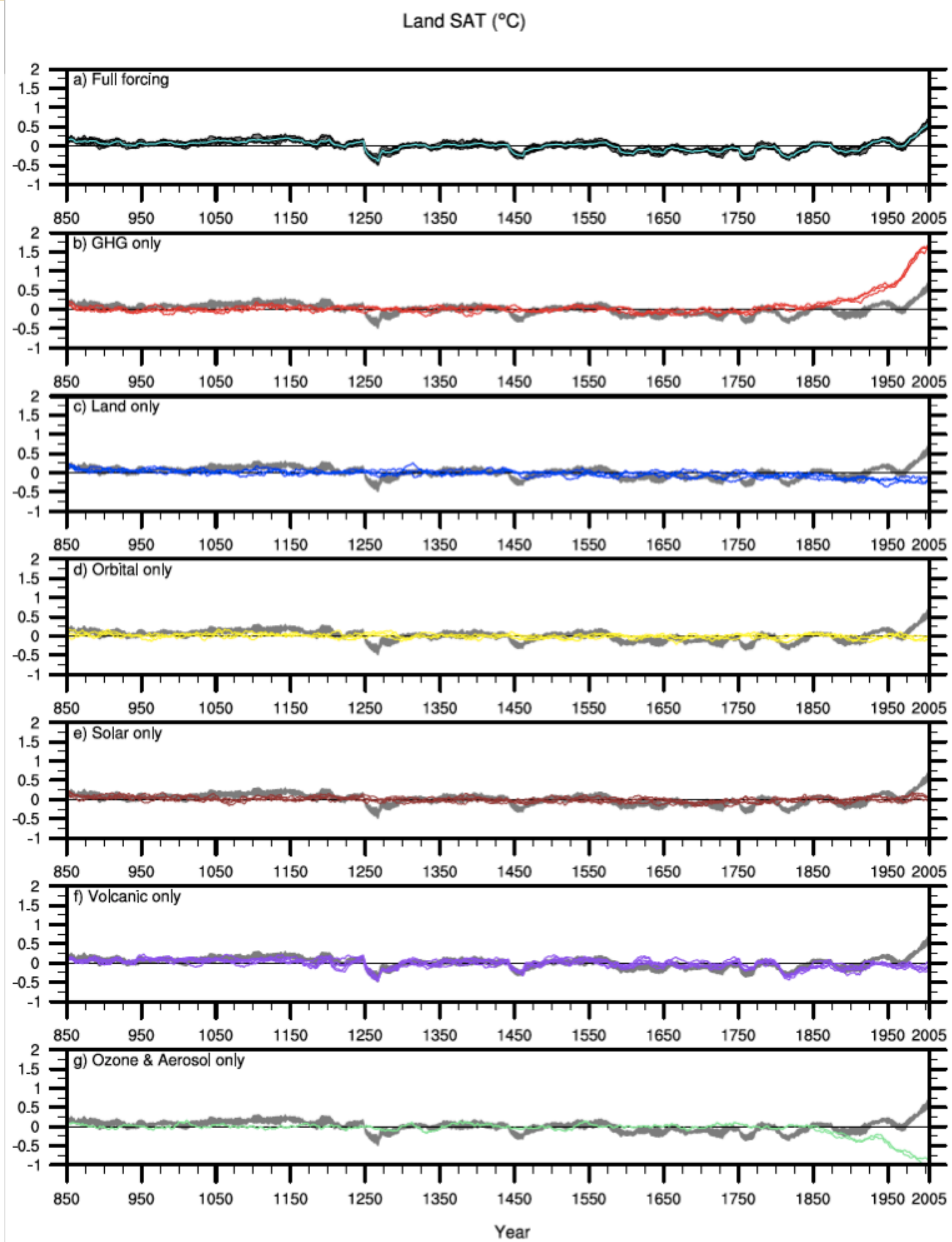
Conclusions (I)

- The climate over land will become drier in a warming world.
- The change in the evaporation over ocean is slower than the change in potential evapotranspiration over land, which leads to a drier terrestrial climate in the future.
- By the end of this century, the world's drylands can be 5.8×10^6 km^2 (or 10 %) larger than in the 1961–1990 climatology.

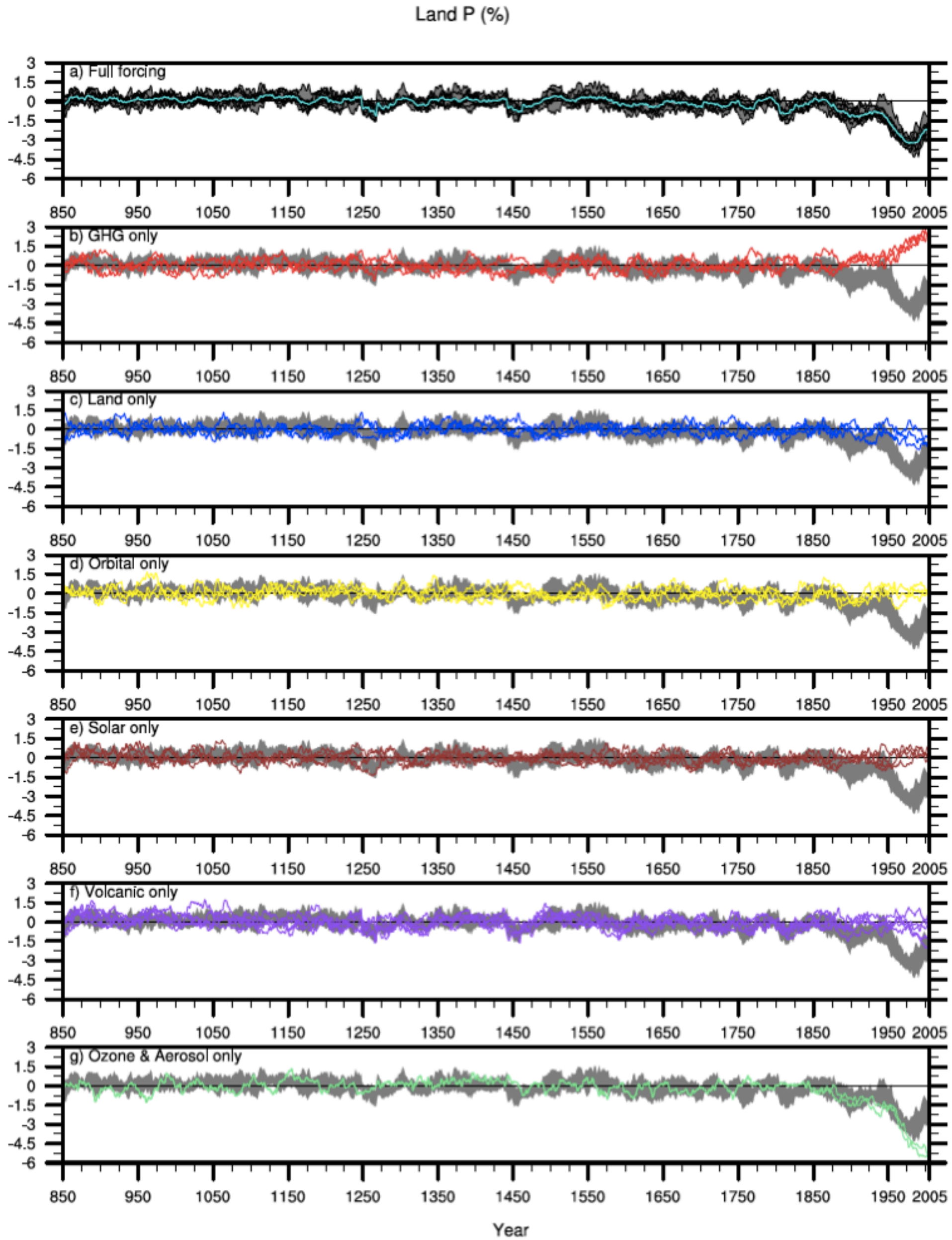
Past, present, future

- CESM-LME simulations for 850-2005 (Otto-Bliesner et al. 2015) and CESM-LE for 1920-2080 (Kay et al. 2014)
- Simulations forced with the transient evolution of solar intensity, volcanic emissions, greenhouse gases, aerosols, land use conditions, and orbital parameters, both together and individually.
- to place anthropogenic changes in the context of changes due to natural forcings during last millennium

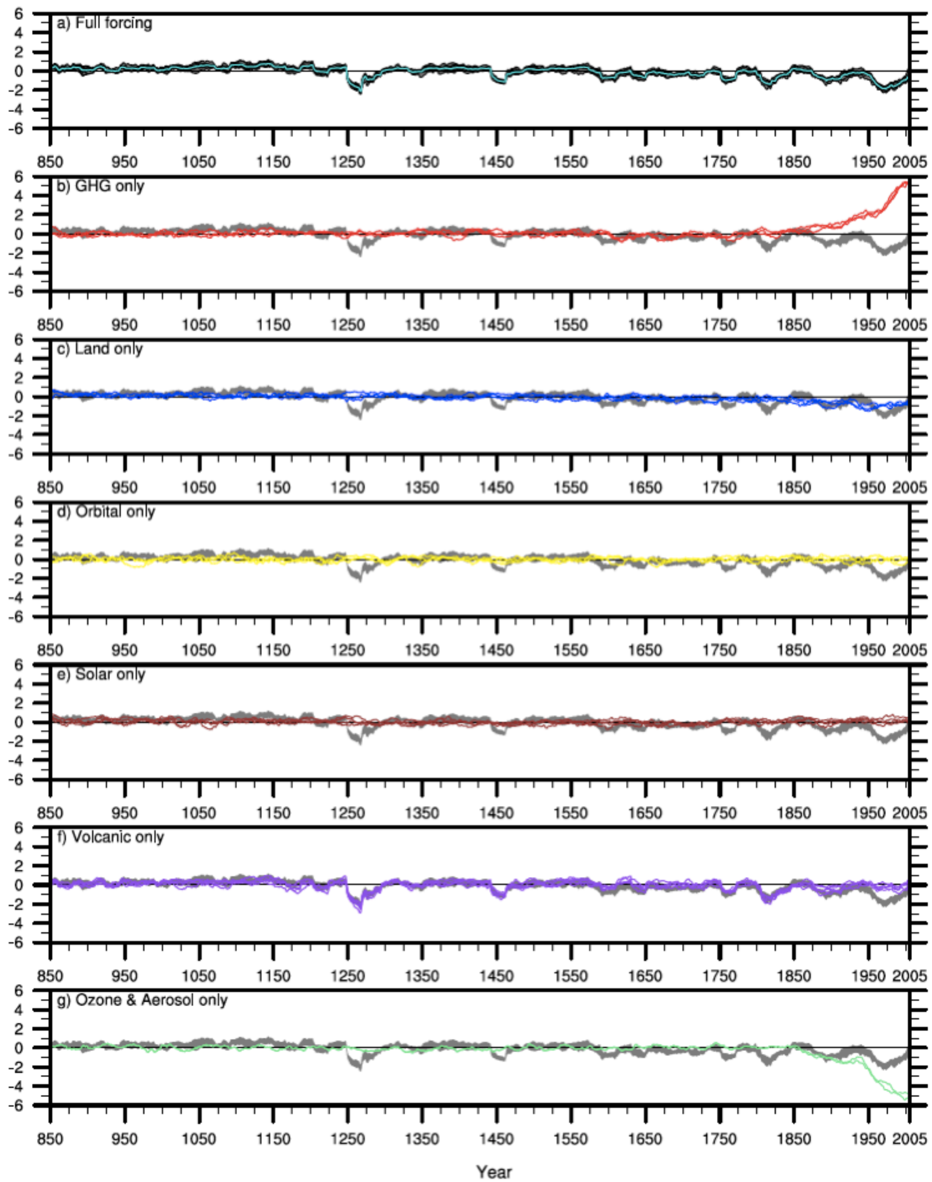

a) Land SAT (°C)
MWP
LIA
PD
b) Land P (%)
c) Land PET (%)
d) Land P/PET (%)
e) Land RH (%)
f) Land Rn - G (W/m2)
g) Land u2 (10^{-2} m/s)
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2005
Year



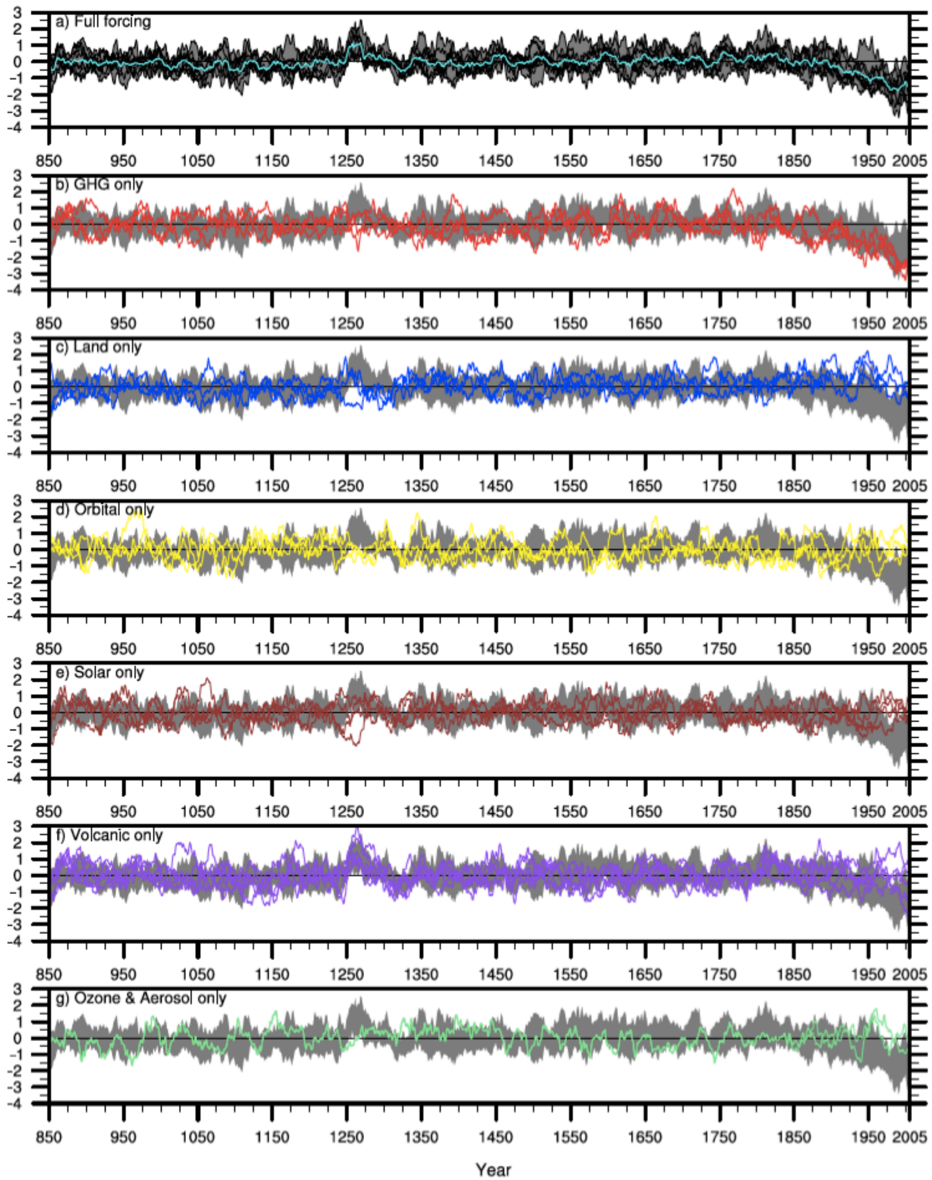
Land SAT (°C)
a) Full forcing
b) GHG only
c) Land only
d) Orbital only
e) Solar only
f) Volcanic only
g) Ozone & Aerosol only
2
1.5
1
0.5
0
-0.5
-1
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2005
Year

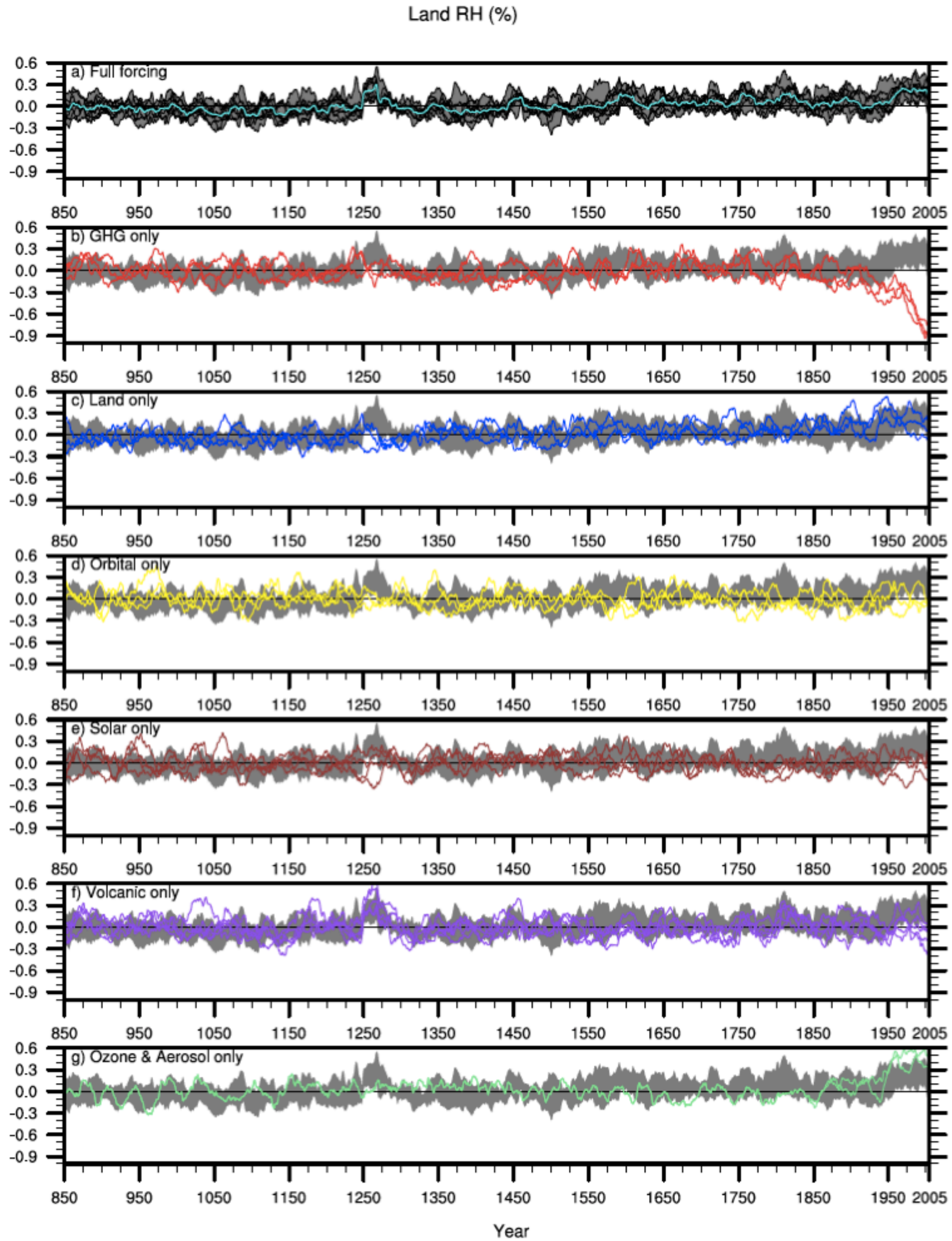

Land P (%)
a) Full forcing
b) GHG only
c) Land only
d) Orbital only
e) Solar only
f) Volcanic only
g) Ozone & Aerosol only
3
1.5
0
-1.5
-3
-4.5
-6
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2005
Year

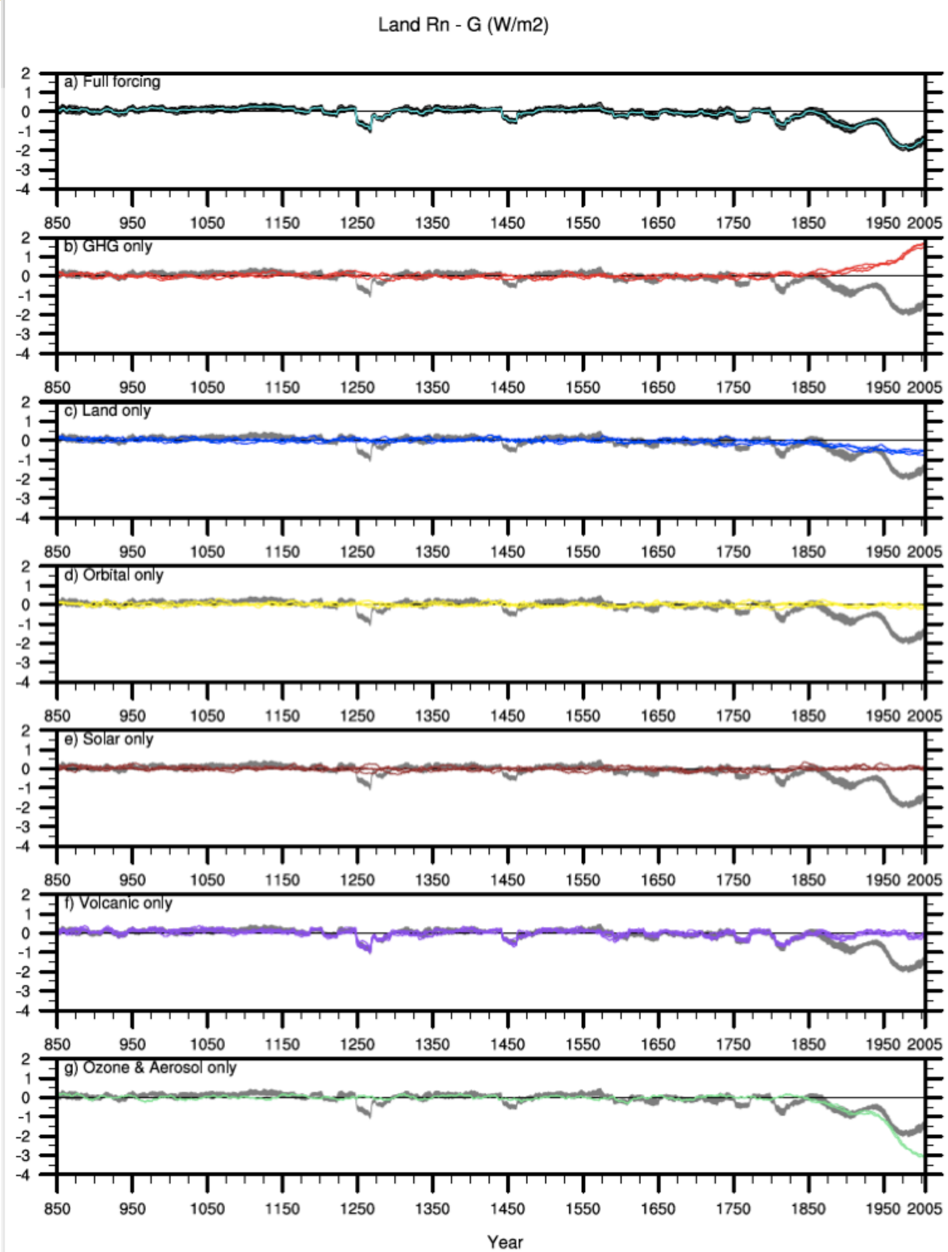
Land PET (%)


a) Full forcing
b) GHG only
c) Land only
d) Orbital only
e) Solar only
f) Volcanic only
g) Ozone & Aerosol only
6
4
2
0
-2
-4
-6
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2005
Year

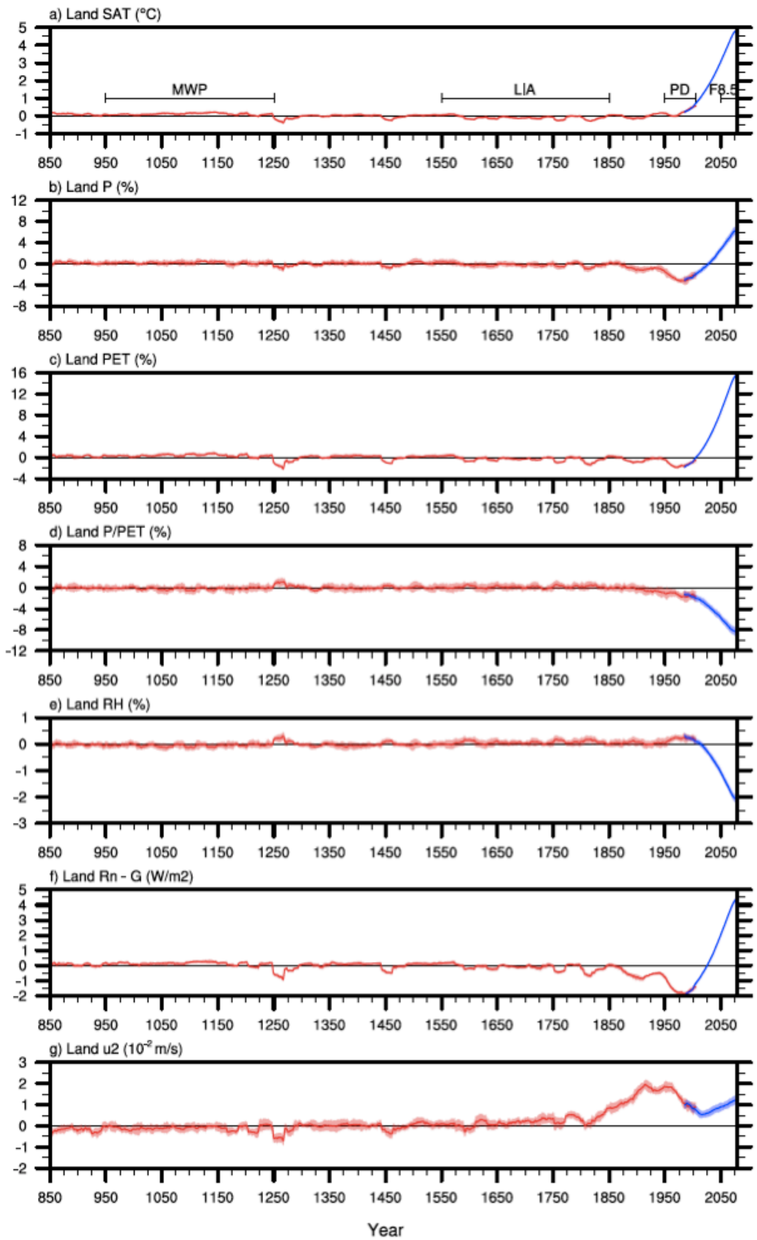
Land P/PET (%)


a) Full forcing
b) GHG only
c) Land only
d) Orbital only
e) Solar only
f) Volcanic only
g) Ozone & Aerosol only
3
2
1
0
-1
-2
-3
-4
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2005
Year


Land RH (%)
a) Full forcing
b) GHG only
c) Land only
d) Orbital only
e) Solar only
f) Volcanic only
g) Ozone & Aerosol only
0.6
0.3
0.0
-0.3
-0.6
-0.9
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2005
Year



Land Rn - G (W/m2)
a) Full forcing
b) GHG only
c) Land only
d) Orbital only
e) Solar only
f) Volcanic only
g) Ozone & Aerosol only
2
1
0
-1
-2
-3
-4
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2005
Year


a) Land SAT (°C)
MWP
LIA
PD
F8.5
b) Land P (%)
c) Land PET (%)
d) Land P/PET (%)
e) Land RH (%)
f) Land Rn - G (W/m2)
g) Land u2 (10^-2 m/s)
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2050
Year

Conclusions (II)

- The aridity index averaged over land, becomes smaller (i.e., a drier terrestrial climate) by 0.34% for MWP versus LIA, 1.4% for PD versus LM, and 7.4% for F8.5 versus LM.
- The terrestrial aridity change in PD-LM is largely driven by greenhouse gas increases. Despite small effects on terrestrial-mean aridity, anthropogenic aerosols totally alter the attributions of aridity changes to meteorological variables by causing large negative anomalies in surface air temperature, available energy, and precipitation.
- This study indicates that geoengineering through solar radiation management could not address the problem of a drier climate caused by greenhouse gas increases.

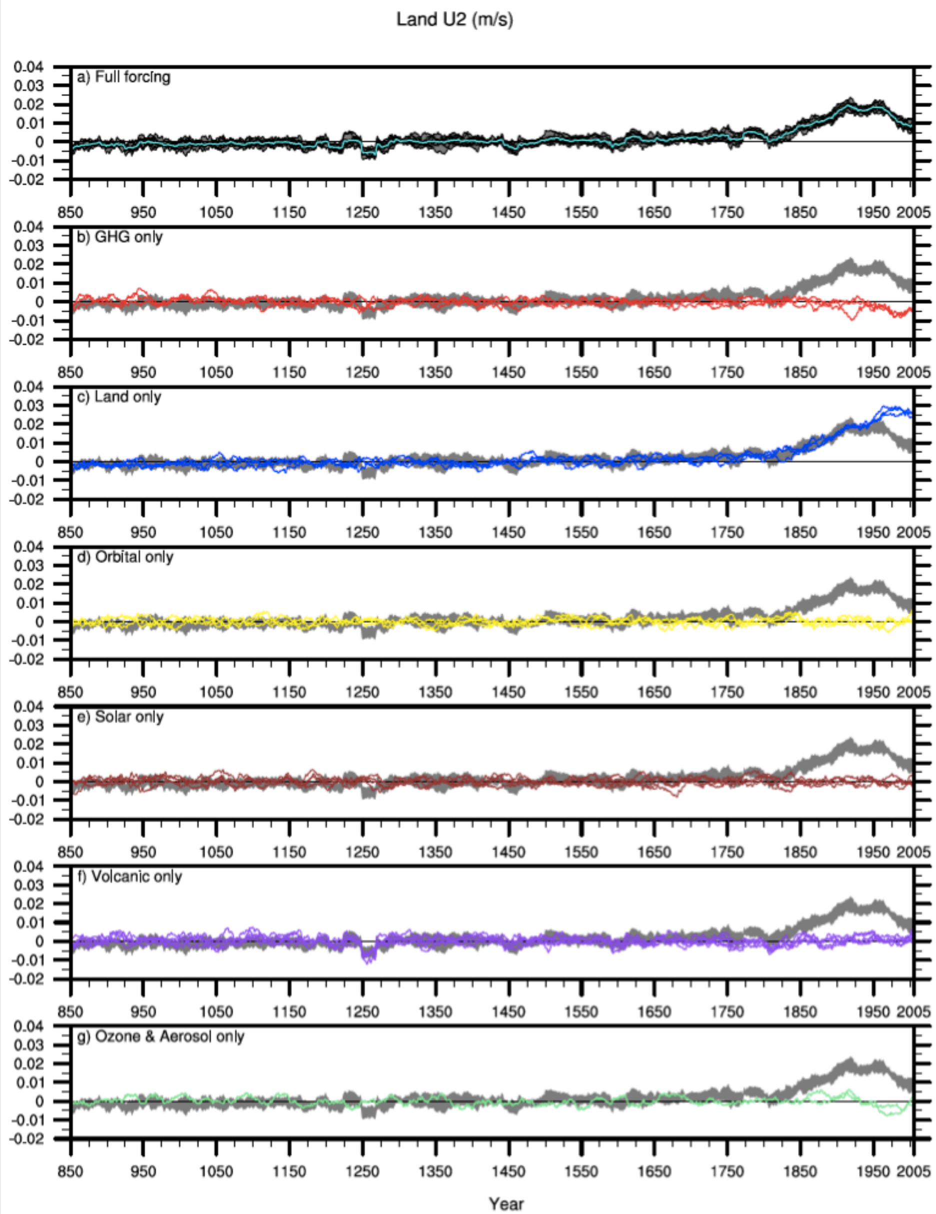
- The PM algorithm was derived from the standard bulk formula for the sensible heat (*SH*) and latent heat (*LH*) fluxes along with the surface energy budget equation

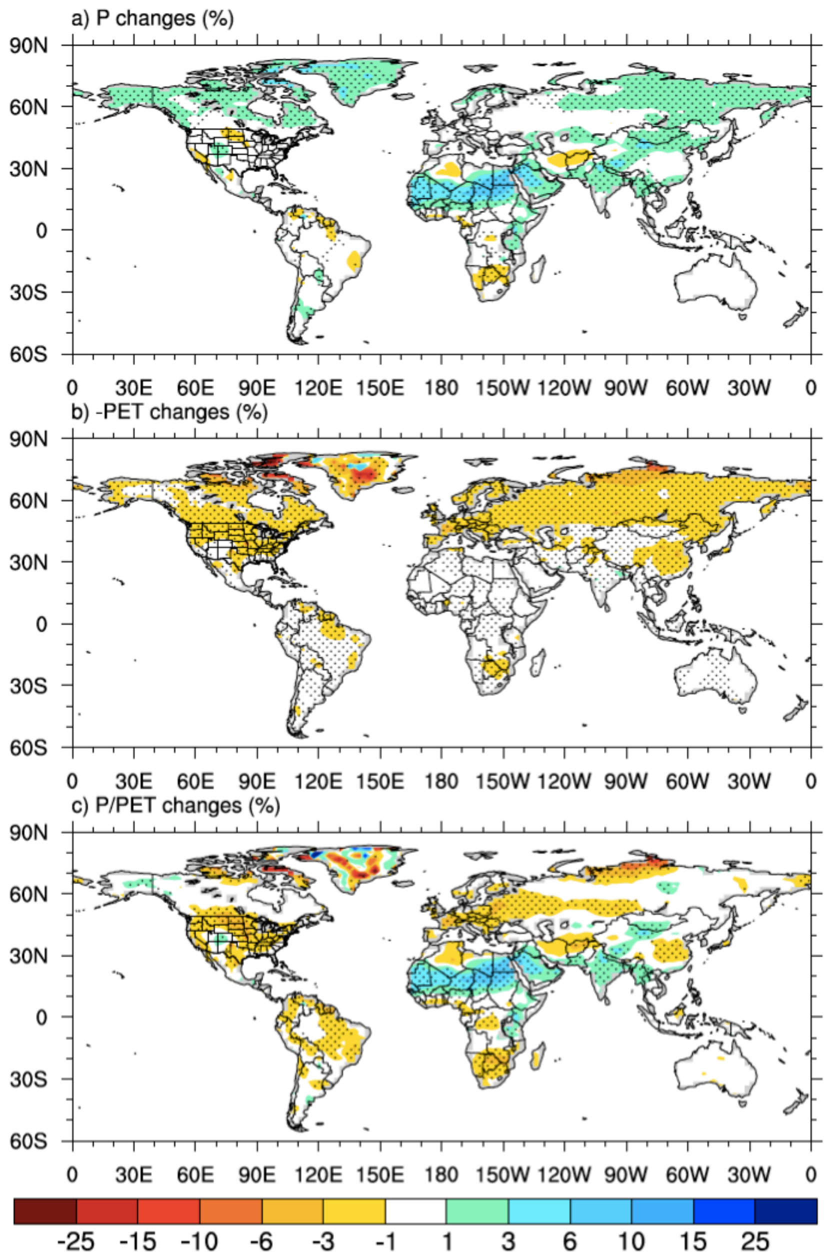
$$SH = \rho_a c_p C_H (T_s - T_a) | u |$$

$$LH = \rho_a L_v C_H (q^*(T_s) - q^*(T_a) RH) | u | / (1 + r_s C_H | u |)$$

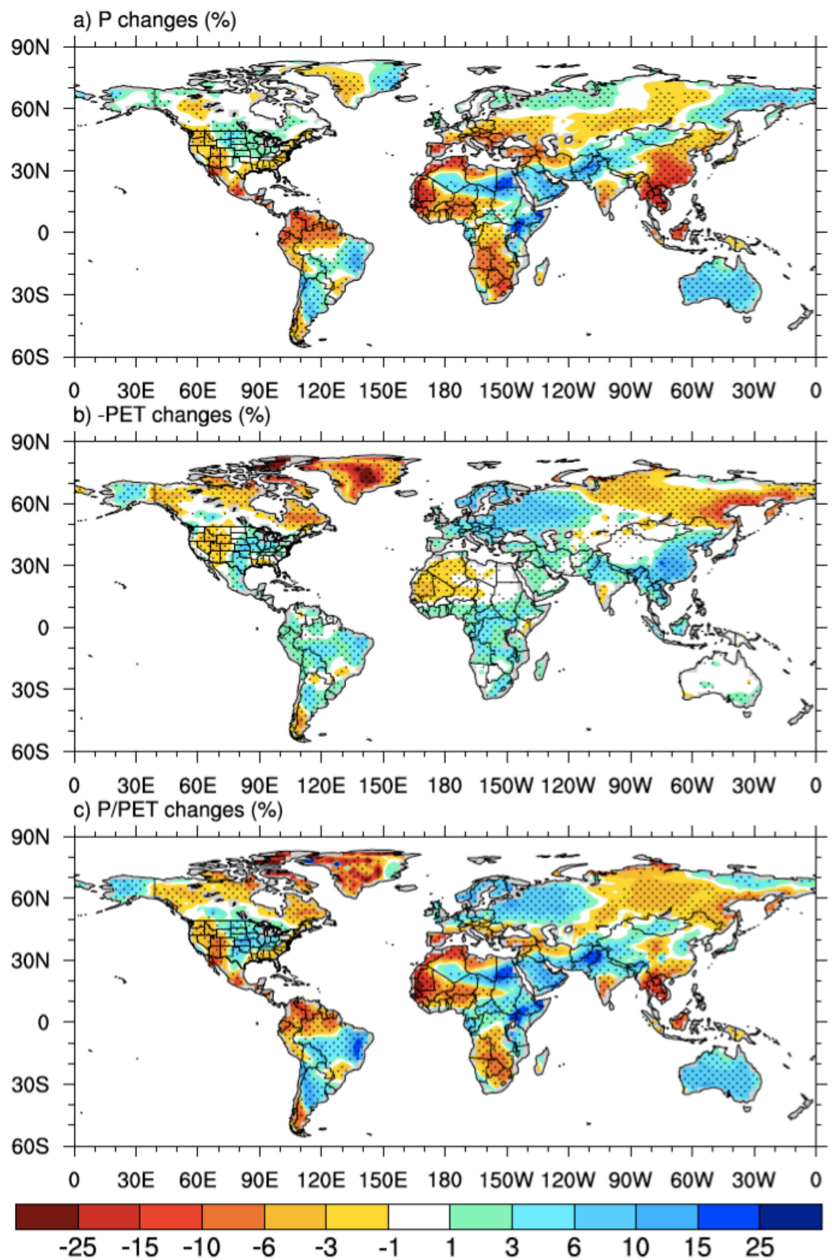
$$R_n - G = SH + LH$$

where T_s is the temperature at the surface interface, $LH = PET^*L_v$, and q^* is the saturated water vapor mixing ratio.


Land U2 (m/s)
a) Full forcing
b) GHG only
c) Land only
d) Orbital only
e) Solar only
f) Volcanic only
g) Ozone & Aerosol only
0.04
0.03
0.02
0.01
0
-0.01
-0.02
850
950
1050
1150
1250
1350
1450
1550
1650
1750
1850
1950
2005
Year



a) P changes (%)
b) -PET changes (%)
c) P/PET changes (%)
90N
60N
30N
0
30S
60S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
-25
-15
-10
-6
-3
-1
1
3
6
10
15
25


a) P changes (%)
b) -PET changes (%)
c) P/PET changes (%)
90N
60N
30N
0
30S
60S
0
30E
60E
90E
120E
150E
180
150W
120W
90W
60W
30W
0
-25
-15
-10
-6
-3
-1
1
3
6
10
15
25